THE FERMILAB LINAC UPGRADE

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Abstract

The Fermilab Linac Upgrade is planned to increase the energy of the H^- linac from 200 to 400 MeV. This is intended to reduce the incoherent space-charge tuneshift at injection into the 8 GeV Booster which can limit either the brightness or the total intensity of the beam. The Linac Upgrade will be achieved by replacing the last four 201.25 MHz drift-tube tanks which accelerate the beam from 116 to 200 MeV, with seven 805 MHz side-coupled cavity modules operating at an average axial field of about 7.5 MV/m. This will allow acceleration to 400 MeV in the existing Linac enclosure. Each accelerator module will be driven with a klystron-based rf power supply. A prototype rf modulator has been built and tested at Fermilab, and a prototype 12 MW klystron is being fabricated by Litton Electron Devices. Fabrication of production accelerator modules is in progress.

Introduction

The Fermilab 200-MeV linear accelerator has operated almost continuously since 1970 as an injector for the Fermilab chain of accelerators and as a secondary neutron producer for the Neutron Therapy Facility with a reliability approaching 99%. The purpose of the Fermilab Linac Upgrade is to increase the final kinetic energy of the beam from 200 MeV to about 400 MeV. This is expected to reduce beam emittance degradation in the 8 GeV synchrotron booster following the linac and allow beams of higher brightness (number of particles per unit emittance) to be accelerated.[1] The intended consequence of this will be to increase the collision rate in the antiproton-proton collider by a factor of three and the intensity for the fixed-target experiments by 75% if the increase in brightness can be conserved through later acceleration stages. The 400-MeV limit is dictated by H^- ion stripping considerations in the magnetic fields of the Linac-to-Booster transfer line.

The present 200 MeV drift-tube linac (DTL) consists of nine accelerator cavities operating at a frequency of 201.25 MHz. Each cavity is powered by a triode-based radio-frequency (rf) power supply rated to deliver up to 5 MW of peak power for a 125 μsec flat-top pulse. The Linac Upgrade will replace the last four cavities, which accelerate the beam from 116 MeV to 200 MeV in a length of 66 meters, with seven side-coupled cavity modules operating at a frequency of 805 MHz or four times the DTL frequency (see Figure 1). The higher frequency allows higher accelerating gradients to be achieved so that a kinetic energy of 400 MeV can be reached in the same linac enclosure. Each module will be driven with a klystron-based rf power supply rated to deliver up to 12 MW of peak power for 125 μsec at 15 Hz repetition rate. The nominal peak power requirement of each module with 35 mA of beam is about 10 MW. The new linac is designed to accelerate up to 50 mA of beam to allow for future improvements.

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Accelerator Structure

The side-coupled accelerating structure (SCS) was selected for the Linac Upgrade because it is well understood and fully proven. The side-coupled structure was used above 100 MeV for the 805 MHz Los Alamos Meson Physics Facility (LAMPF) proton linac designed in the early 1960's (see Figure 2). This coupled-cavity structure is operated in a so-called TM_{010} $\pi/2$ standing wave mode in which the phase shift between an accelerating cell and an adjacent coupling cell (off the beam axis) is 90 degrees. The accelerator cell length is $\beta\lambda/2$ for particle-wave synchronism. Here β is the particle velocity divided by the speed of light, and λ is the free space wavelength of the accelerating field. The insensitivity of field amplitudes and phases to mechanical perturbations in such $\pi/2$ structures is a fundamental reason for their widespread use.

From the work done at Los Alamos National Laboratory on the SCS and the Fermilab program of design,[2] tuning,[3] prototyping[4] and full-power testing,[5] we have confidence that our design goals can be met. Because the new side-coupled (SC) linac will replace that part of the existing drift-tube linac which accelerates the beam from 116 MeV to 200 MeV, it must have a gradient about three times higher than in the DTL and make conservative use of space for beam matching, focusing and diagnostics. In particular, a Transition Section for matching the beam between the DTL and side-coupled linac and a space of about two meters at the downstream end of the linac for changes in the Linac-to-Booster transfer line are required. Other major design goals were to minimize power consumption and to keep all parameters within a range favoring dependable routine operation. Table 1 summarizes the principle design criteria and derived parameters for the new linac.

The average axial field, E_o of 7.5 MV/m is about three times the gradient in the existing DTL. Long voltage conditioning times and an inordinately high sparking rate causing erratic beam pulses and unreliable injector operation are considered unacceptable for the new linac. For the Linac Upgrade it was considered desirable to limit the spark rate to one spark per thousand rf pulses corresponding to at most 0.1% beam loss due to cavity sparking. To investigate this constraint, full power testing has been performed on six-cell prototype cavities and a complete 16-cell accelerator section.[5] The later represents one of the 28 sections needed for the new linac. These power tests have shown that with the appropriate cavity nose-cone shape (see Figure 3) to reduce peak surface fields (37 MV/m), a spark rate of one spark per thousand rf pulses can be achieved for a complete linac after about 20 million rf pulses (125 μsec, 15 Hz) of conditioning. The spark rate continues to decrease with conditioning. Over the range of surface fields 30 to 45 MV/m, the spark rate varies as $E_s^{19.5 \pm 0.5}$.

Table 1. 400 MeV Linac Design Criteria and General Parameters

Initial kinetic energy (T_i)	116.54	MeV
Final kinetic energy (T_f)	401.46	MeV
Length, including transition section	63.678	m
Frequency of rf (f)	805.0	MHz
Beam current averaged over pulse (I_b)	50.	mA
Beam pulse length	< 100.	μs
Repetition rate	15.0	Hz
Accelerating phase (φ_s)	-32.	deg
Average axial field (E_o)	8.07–7.09	MV/m
Maximum surface field (E_{max})	36.8	MV/m
Kilpatrick limit (E_K)	26.	MV/m
Number of modules	7	
RF power/module, typical	< 12.	MW
copper loss	7.2	MW
beam power	2.0	MW
reserve and control	2.8	MW
Number of sections/module	4	
Number of rf cells/section	16	
Total number of rf cells ($7 \times 4 \times 16$)	448	
Length of bridge couplers between sections	$\frac{3}{2}\beta\lambda$	
Transverse focusing scheme	FODO	
Transverse phase advance/FODO cell, average	79.	deg
Quadrupole magnetic length	8.0	cm
Quadrupole poletip field	4.6	kG
Quadrupole bore radius (r_q)	2.0	cm
Cavity bore radius (r_b)	1.5	cm

The rf properties of accelerating cells for the SC linac were calculated with the computer code SUPERFISH. Cavity dimensions were determined generally to maximize the shunt impedance for all energies. The major cavity radius R_c basically determines the shunt impedance, but several other dimensions were varied to slightly improve this parameter. A constant cavity radius of 13.455 cm was found to be adequate between 116 and 400 MeV. To reduce peak surface fields while concentrating more field into the accelerating gap, a double-radius nose-cone design was adopted.[6] Here the nose-cone outline is determined by two radii of curvature, 7 mm and 2.21 mm. The program SUPERFISH was used to calculate the effective shunt impedance ZT^2, the transit time factor T, and the ratio of the maximum surface field and average accelerating field E_{max}/E_o at several values of β corresponding to the energy range 116 to 400 MeV. The SUPERFISH values of ZT^2 (see Figure 4) are typically 15% lower in actual cavities due to the coupling slot (5% coupling) and braze imperfections.

The division of the new SC linac into seven independently excited rf modules originally resulted from three principal considerations, namely the practical size for 805 MHz klystrons, the shunt impedance of the structure and the existence of suitable penetrations from the linac utility basement into the linac enclosure. Since the original design in 1987, radiation safety considerations have mandated the need for new waveguide penetrations with the existing downstream DTL penetrations in the linac utility basement to be ultimately sealed. Uniform distribution of rf power favors feeding the modules from the center, so there is a bridge coupler at that location which can accommodate a magnetic quadrupole also. Rf defocusing requires that the quadrupoles of the FODO channel be less than two meters apart in the first modules. These conditions were satisfied by dividing the modules into four sections separated by bridge couplers of length $3\beta\lambda/2$ (see Figure 5).

The linac design proceeded interatively by using third order fits to ZT^2, T and E_{max}/E_o to calculate the length and number of cells needed to reach the design energy of 400 MeV. The design was subject to the constraints that the peak electric field not exceed 44 MV/m (1.6 Kilpatrick), the accelerating cells in each section be of constant length and that the total length of the side-coupled linac not exceed 66 meters. An acceptable design was arrived at by having 16 cells per section with peak fields of only 37 MV/m and roughly equal power dissipation in each section. Table 2 summarizes the parameters of the side-coupled linac by accelerator section. Module 0, Sections 1 and 2 are the two 805 MHz buncher cavities in the Transition Section between the DTL and new linac.

Table 2. 400 MeV Linac Parame ers by Section

Module /Sect.	Grad. [MV/m]	KE_{out} [MeV]	L_{rf} [m]	L_{sep} [m]	P_{cu} [MW]	P_{beam} [MW]	$\Delta\phi_{x,y}$ [deg]	$\Delta\phi_z$ [deg]
0					(Transition Section)			
1	2.23	116.5	1.3613	0.6653	0.13	0.00		
2	0.00	116.5	0.3403	0.7951	0.00	0.00		
			0.0000	0.8381				
			1.7016	2.2984	0.13	0.00		
			4.0000		0.13			
1	8.07							
1		125.1	1.3814	0.1418	1.75	0.43		
2		133.8	1.4215	0.2628	1.88	0.44	77	109
3		142.8	1.4606	0.2703	1.93	0.45		
4		152.1	1.4987	0.2775	1.91	0.46	78	106
			5.7621	0.9524	7.47	1.78		
			6.7145		9.25			
2	7.85							
1		161.2	1.5353	0.2846	1.72	0.46		
2		170.6	1.5704	0.2912	1.85	0.47	80	103
3		180.2	1.6047	0.2977	1.88	0.48		
4		190.0	1.6380	0.3041	1.88	0.49	80	101
			6.3484	1.1776	7.33	1.90		
			7.5260		9.23			
3	7.66							
1		199.7	1.6700	0.3102	1.70	0.48		
2		209.5	1.7009	0.3161	1.82	0.49	91	98
3		219.6	1.7309	0.3218	1.86	0.50		
4		229.8	1.7600	0.3273	1.85	0.51	81	96
			6.8618	1.2754	7.23	1.98		
			8.1372		9.21			
4	7.48							
1		239.9	1.7881	0.3327	1.68	0.51		
2		250.1	1.8151	0.3379	1.79	0.51	81	94
3		260.5	1.8414	0.3428	1.84	0.52		
4		271.1	1.8670	0.3477	1.83	0.53	80	92
			7.3116	1.3611	7.14	2.07		
			8.6728		9.21			
5	7.34							
1		281.5	1.8917	0.3524	1.67	0.52		
2		292.1	1.9155	0.3570	1.78	0.53	80	90
3		302.8	1.9387	0.3614	1.83	0.53		
4		313.6	1.9613	0.3657	1.81	0.54	79	89
			7.7072	1.4365	7.09	2.12		
			9.1436		9.21			
6	7.20							
1		324.4	1.9830	0.3698	1.66	0.54		
2		335.2	2.0039	0.3738	1.77	0.54	79	87
3		346.1	2.0244	0.3777	1.81	0.55		
4		357.1	2.0443	0.3815	1.79	0.55	78	85
			8.0555	1.5028	7.03	2.18		
			9.5583		9.21			
7	7.09							
1		368.1	2.0635	0.3852	1.65	0.55		
2		379.1	2.0821	0.3887	1.76	0.55	77	84
3		390.2	2.1002	0.3921	1.80	0.56		
4		401.5	2.1179	0.3955	1.78	0.56	76	82
			8.3637	1.5614	6.99	2.22		
			9.9251		9.21			
Grand			52.1119	11.5656	50.27	14.25		
Total			63.6775		64.66			

For the bridge coupler, the post-stabilized design originally developed for the LAMPF accelerator has been adopted.[7] The $3\beta\lambda/2$ couplers for the Linac Upgrade range in length from about 35 cm to 55 cm and are shorter than any used at LAMPF ($5\beta\lambda/2$ and $7\beta\lambda/2$). Bridge coupler models and MAFIA[8] computer calculations indicate that the use of two side-posts, 90 degrees apart, permits the interfering $TE_{111}(x,y)$ and $TM_{011}(x,y)$ modes to be moved out of the accelerating passband (780-830 MHz for 5% coupling). The bridge couplers will have two end-posts for tuning the fundamental TM010 resonance.

The DTL operates with stronger transverse focusing and weaker longitudinal focusing than the side-coupled linac. Six-dimensional phase space matching is required to preserve the brightness of the DTL beam in the new linac. The longitudinal matching is effected by placing a sixteen-cavity, 805 MHz side-coupled buncher section (E_0T = 2 MV/m) after the last drift-tube tank (Tank 5) and a four-cavity vernier buncher half-way between the sixteen-cavity buncher and first section of the new linac (see Figure 6). The last two DTL quadrupoles and three new quadrupoles separating the DTL, bunchers and new linac will control the transverse matching. The total length of the Transition Section is about four meters. The 805 MHz bunchers will probably be powered by 200 kW Varian VKP-7955 klystrons.

Radio-Frequency Power System

The 805 MHz Linac Upgrade requires seven high-power klystron and modulator systems to run the seven independent accelerator modules. Table 3 gives a complete power tabulation for an RF station assuming 35 mA of accelerated beam. This shows that only about 10 MW of peak power is needed. The klystron specifications in Table 4 apply to a 12 MW prototype klystron on order with Litton Electron Devices. The RF modulator consists of a pulse forming network (PFN) discharged into the klystron cathode through an oil-filled 20:1 step-up transformer. The PFN is charged to 18 kV from a power supply using the resonant charging technique (capacitor and charging choke) with an SCR (silicon controlled rectifier) switch to initiate the charging cycle. The power supply stores about 40 kJ but only about 6 kJ are used to charge the PFN every 66 msec (15 Hz).

Table 3. RF Power Tabulation

Nominal power, accelerating 35 mA beam (SUPERFISH shunt impedance derated by 15%)	8.6 MW
Waveguide run losses (WR975), harmonic isolator (if required)	0.6 MW
Add 10% for feedback loop regulation	0.9 MW
The cavity diameter may have to be altered slightly at some β's to avoid TM_{110} deflecting modes	0.1 MW
Estimated Total	10.2 MW

Table 4. Klystron Specifications

Peak power output	12 MW
Pulse length	125 μs
Pulse repetition rate	15 pps
Duty factor	0.1875%
Average power	22.5 KW
Efficiency	50%
Gain	50 dB
RF output	WR975 waveguide
Dimensions	108 inch height 24 inch diameter
Voltage	170 KV
Current	141 A

Project Status

The three major systems for the Linac Upgrade are side-coupled accelerator modules, rf modulators and 12 MW klystrons. The Project began construction in October 1989 and is scheduled for linac conversion to 400 MeV energy in the summer of 1992. A prototype rf modulator begun in January 1989 was successfully operating into a resistive load by December 1989. The modulator can produce up to 40 MW of power for 125 μsec pulses at 15 Hz. Some design modifications were made based on the operation of this prototype, and component procurement for the seven production modulators began in April 1990. Fabrication is scheduled to begin in November 1990 and be completed by October 1991.

Fabrication of a prototype accelerator module (four sections and three bridge couplers) began in October 1989. This prototype is electrically and mechanically equivalent to the first of seven side-coupled linac modules needed for the new linac. The first 16-cavity section was brazed at Pyromet Inc. (San Carlos, California) in January 1990 and the second section in April. The third and fourth sections were brazed simultaneously in August 1990. The first section brazed was power tested and voltage conditioned to design gradient in April 1990. Buildup of the sections and bridge couplers into a complete module began in August 1990. This prototype is now planned to be used as the first accelerator module of the new linac.

In June 1990 Class 1, OFHC copper segments for production accelerator fabrication began arriving from Hitachi Industries, Japan. Copper for one 16-cavity linac section arrives every two weeks to begin a four-month machining, tuning and brazing cycle (see Ref. 4). The segmented construction of side-coupled accelerating structure used at LAMPF has been adopted for the Fermilab linac (see Figure 7). As of September 1990 seven sections of copper had arrived and the fabrication cycle was on schedule. Two sections will be brazed every four weeks at Pyromet Inc. starting in October 1990. When brazed sections return to Fermilab, the $\pi/2$ mode is tuned to within 20 kHz of 805 MHz (as corrected for 25°C and vacuum) and the side-cells are tuned to give a 100 kHz positive stopband for thermal stability (see Ref. 3).

A prototype 12 MW klystron is on order with Litton Electron Devices, San Carlos, California. The L-5859 klystron has five cavities (input, two idlers, penultimate, output) and should operate at 2 μperv. The prototype was due in December 1989. In January 1990 while under test at the plant, the tube suffered a catastrophic arc destroying the barium-strontium coated cathode. The cathode had not been adequately processed and the tube's 1.5 liter/sec ion pump was inadequate (subsequently changed to an 8 liter/sec pump). A rebuilt klystron was delivered to Fermialb in May 1990. The tube reached 12 MW power with a gain exceeding 50 dB (see Figure 8). After about 18 hours of rf running the tube suffered a loss of vacuum. Failure analysis at Litton indicated a ceramic arc punch-through in the high-voltage cathode insulator. The tube was dissasembled and cleaned with rebuilding in progress as of September 1990. The prototype and subsequent production tubes are on the critical path for the project's completion.

References

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8. T. Weiland, "Computer Modelling of Two and Three-Dimensional Cavities", IEEE Trans. Nucl. Sci. NS-32, 2738 (1985).

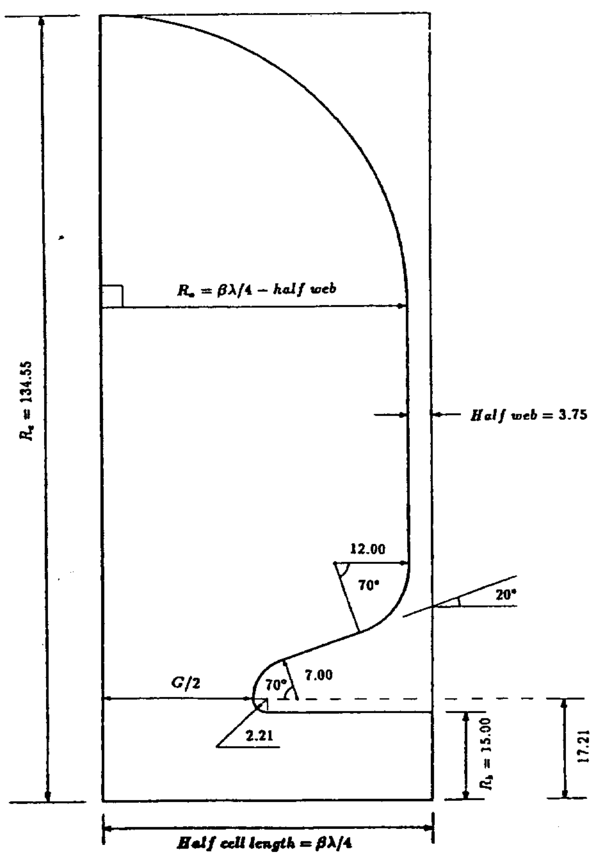

Figure 3. Fermilab 805-MHz side-coupled cavity geometry (dimensions in mm).

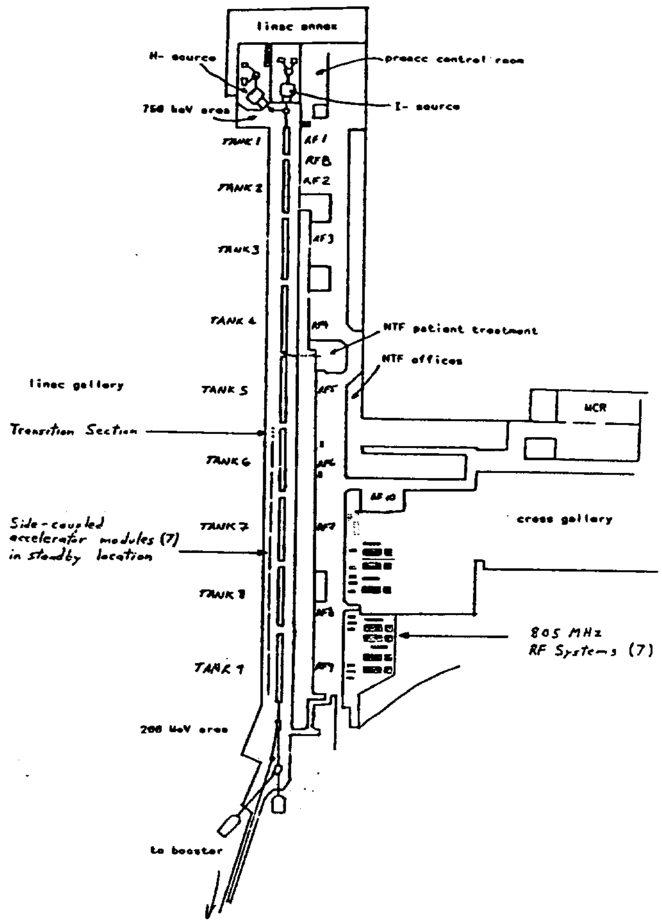

Figure 1. The Fermilab Linac (plan view)

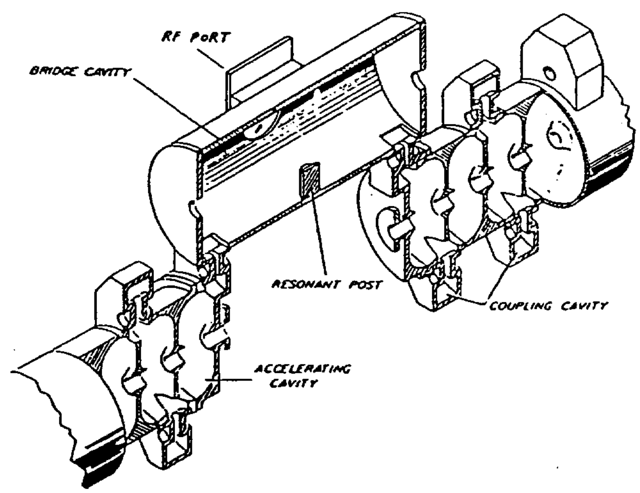

Figure 2. The LAMPF side-coupled accelerator and post-stabilized bridge coupler.

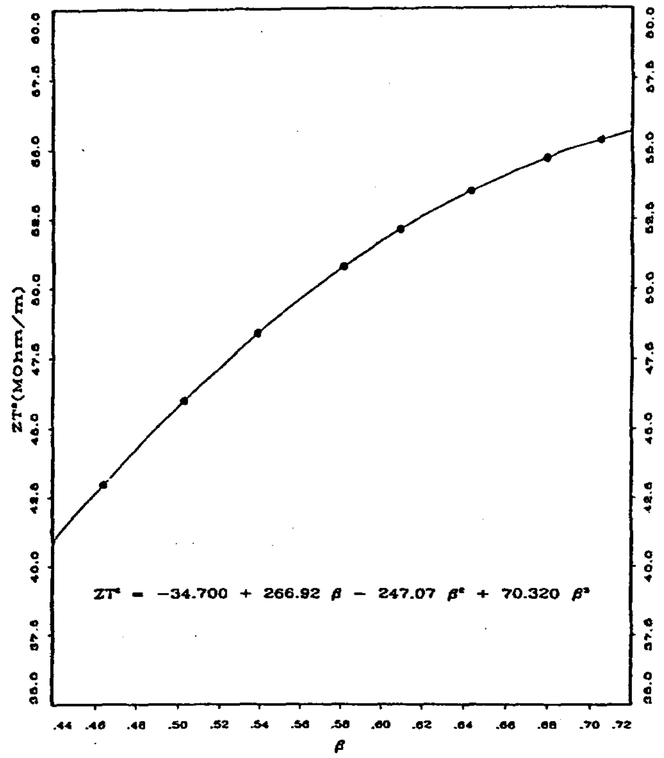

Figure 4. Effective shunt impedance versus relativistic beta for the Fermilab side-coupled linac (unadjusted SUPERFISH calculation).

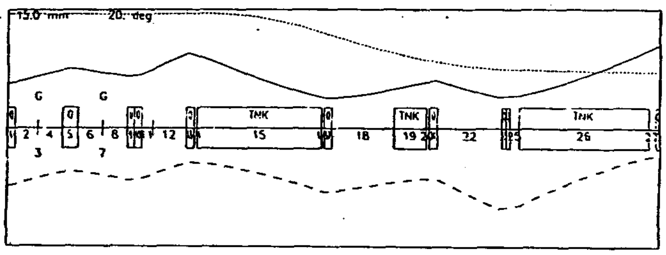

Figure 6. Transition Section beam envelopes from the center of the third from last quadrupole in DTL Tank 5 to the center of the quadrupole between Sections 1 and 2 of side-coupled Module 1. The bunch length is shown with a dotted curve, the horizontal envelope with a solid curve and the vertical envelope with a dashed curve.

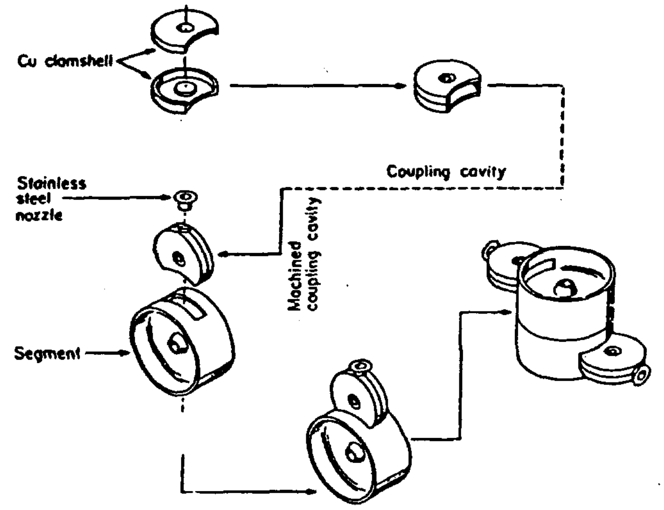

Figure 7. Segmented construction of side-coupled accelerator structure used for the LAMPF and Fermilab linacs.

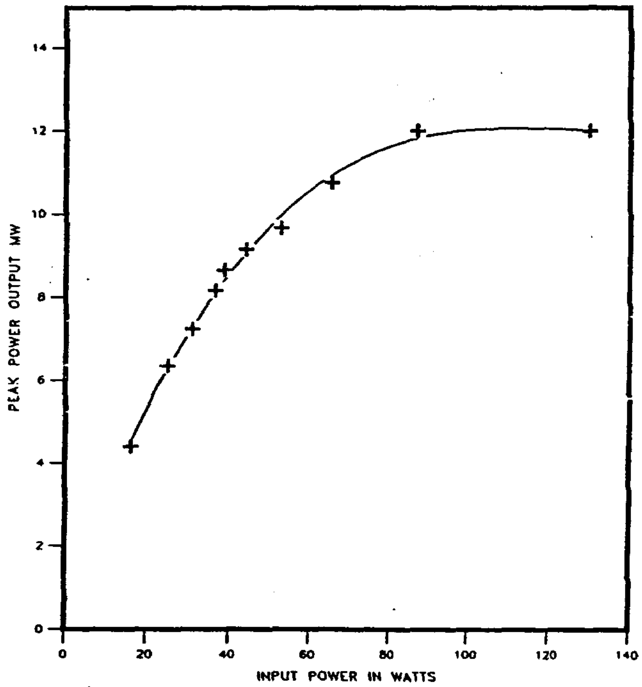

Figure 8. Peak power output versus input drive power for the Litton L-5859 805 MHz klystron.

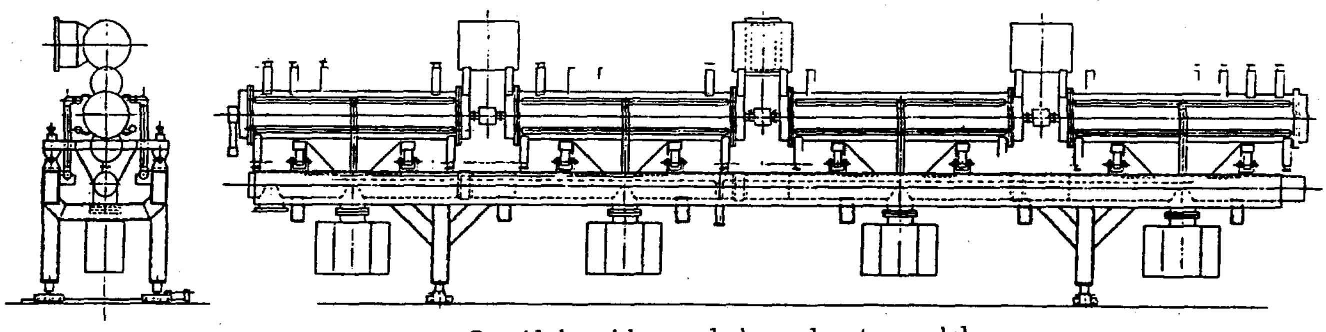

Figure 5. Fermilab side-coupled accelerator module containing four sections and three bridge couplers. Module height is approximately 2 meters, and the length varies from 6.5 to 10 meters for Modules 1 to 7.